MAGNETIC SPECTROMETER CALIBRATION FOR GAMMA-RAY INTENSITIES

MAGNETIC SPECTROMETER CALIBRATION FOR GAMMA-RAY INTENSITIES

By

Anne Vivian Staveley, B.Sc.

A Thesis

Submitted to the Faculty of Graduate

Studies in Partial Fulfilment of the

Requirements for the Degree

Master of Science

McMaster University

October 1961

MASTER OF SCIENCE (1961)
(Physics)

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Magnetic Spectrometer Calibration for Gamma-Ray Intensities

AUTHOR: Anne Vivian Staveley, B.Sc. (Bishop's)

SUPERVISOR: Professor M. W. Johns

NUMBER OF PAGES: v, 39

SCOPE AND CONTENTS: A study has been made of the external conversion spectrum of gamma-rays of less than 200 kev. A set of semi-empirical curves relating the photoelectric peak height to the gamma-ray intensity has been established using antimony radiators. These results will be discussed.

A method of preparing thin beta sources will also be described.

ACKNOWLEDGEMENTS

I wish to express my sincere thanks to Dr. M. W. Johns for his continual help and guidance during my course of study at this University.

I am indebted to Dr. Agda Artna for her patient explanations and assistance. Thanks are also due to all members of the Beta- and Gamma-Ray Spectroscopy group for helpful discussions and ideas.

The financial assistance of the National Research Council in the form of a bursary is gratefully acknowledged.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I. SOME THEORETICAL CONCEPTS OF GAMMA RADIATION

Introduction

A great deal of what is known of the structure of the nucleus has been obtained by studying the radiations that radioactive nuclei emit. These radiations are of three types: alpha (α), beta (β) and gamma (γ). Alpha particles are heavy and positively charged. They are emitted in monoergic groups and they interact strongly with matter.

Beta particles do not interact so strongly with matter. They are emitted with a continuous spectrum of energy from 0 to E_{mx}, the total energy of the transition. The remaining energy is carried away by the neutrino, a massless particle which interacts very little with matter. The nucleus may also emit monoergic groups of electrons. These are now known to be due to the internal conversion of gamma rays. Internal conversion will be discussed later in this Chapter.

The third type of radiation (gamma) is electromagnetic radiation which interacts with matter to eject electrons which can then be observed experimentally. This radiation is associated with a transition of a nucleus to a lower energy state. An excited nucleus may emit many gamma rays before reaching the ground state. A study of these gamma rays and their relative intensity can provide valuable information about the structure of the nucleus.

One of the most useful instruments in the study of beta and gamma rays is the beta-ray spectrometer. This thesis will describe a method of

preparing beta sources for this instrument. It will also be concerned with the preparation of antimony radiators and their application to the study of the intensity of low energy gamma rays.

(A) Definition of Spin and Parity

To describe a nuclear level it is necessary to give its energy relative to the ground state and its spin and parity. Each nucleon possesses angular momentum due to its orbital motion within the nucleus and also an intrinsic spin of $1/2\,\hbar$. The spin and orbital angular momentum add vectorially to give the total angular momentum of the nucleon. The nuclear angular momentum or "spin" is the vector sum of the angular momenta of all its nucleons. The nuclear spin is an integral or half-integral multiple of $\hbar$ according as the mass number is even or odd. When a nucleus is in an excited state the spin may differ from the ground state value.

A system is said to have positive or even parity if the wave function, ψ, describing it obeys the equation

$$\psi(x, y, z) = \psi(-x, -y, -z)$$

If

$$\psi(x, y, z) = -\psi(-x, -y, -z)$$

the system has negative or odd parity.

Spin and parity cannot be measured directly but can be deduced from a study of transitions to other levels. It is the business of the beta spectroscopist to determine the position and character of these nuclear levels.

(B) Gamma Radiation

A nucleus in an excited state may reach a lower energy level (which may or may not be the ground state) by the emission of a gamma ray. The energy of the gamma ray emitted is equal to the energy difference between

the initial and final states of the nucleus. Gamma rays are classified according to their multipole order and to the parity change (if any) of the nucleus during the transition.

The multipole order, n, of a gamma ray is equal to the vector change (in units of $\hbar$) of the nuclear spin. Thus it follows that

$$|J_i - J_f| \leq n \leq |J_i + J_f|$$

where J_i and J_f are the spins of the initial and final states respectively. Transitions from $J_i = 0$ to $J_f = 0$ are forbidden. The lowest order transition ($= |J_i - J_f|$) is the most probable except in the case of some nuclei in which collective motion becomes important. In these higher order transitions may be enhanced. The types of radiation are classified in Table I according to multipole order, parity change and relative probability. The probability of a transition decreases by about two orders of magnitude in moving from column to column in the Table.

TABLE I

Possible Types of Gamma Radiation

Multipole Order	1	1	2	2	3	3	4	4
Parity Change	E1			M2	E3			M4
No Parity Change		M1	E2			M3	E4	

It is clear that a study of the multipole character of gamma transitions can yield useful information about the nuclear levels involved.

(C) Internal Conversion

Instead of emitting a gamma ray, a nucleus may de-excite by transferring energy to one of its orbital electrons. The electron is then emitted with energy E_e equal to the energy of the transition less the electron binding energy. Internal conversion is most probable for the tightly bound K-shell electrons but L, M and higher-orbit electrons can also be converted. The total internal conversion coefficient α_T is defined by

$$\alpha_T = N_e / N_\gamma$$

where N_e is the number of conversion electrons and N_γ, the number of gamma rays emitted. α_T decreases rapidly as the energy of the transition increases and is higher for higher multipole-order transitions. α_T is the sum of the partial conversion coefficients α_K, α_L, ... etc. α_K is the ratio of the number of K-shell electrons to the number of gamma rays emitted. α_L is similarly defined. The values of these partial conversion coefficients change radically with multipole character and energy. Hence, a study of the relative and absolute intensities of the internal conversion electron groups provides a powerful means of determining the properties of the nuclear levels involved.

(D) The Interaction of Gamma Rays with Matter

The intensity of a beam of gamma rays that has traversed a layer of matter of mass m per sq. cm. is given by

$$I = I_o e^{-\mu m}$$

where I_o is the initial intensity of the beam. μ, the total mass absorption coefficient, is dependent upon the absorbing material and the energy of the incident gamma rays. μ can be broken down into three components,

τ, σ and π. τ, σ and π are the mass absorption coefficients due to the photoelectric effect, compton scattering and pair production respectively. Each of these effects will now be discussed separately.

(i) The Photoelectric Effect

An incident gamma ray may interact with an atom of the absorber and transfer its total energy to an orbital electron of that atom. This process is known as the photoelectric effect.

The presence of the atom is needed to conserve momentum and, hence, the photoelectric effect cannot occur for free electrons. The photoelectric cross section is dependent upon the absorbing material and the gamma-ray energy. Heitler (1944) estimated that τ varies as Z^5 and $E_\gamma^{-3.5}$. This is true in the limited case where $I_K \ll E_\gamma \ll M_o C^2$ and only K-shell electrons are emitted. I_K is the K-shell binding energy. Accurate measurements of the photoelectric cross section have been made and tables are available (e.g. Seigbahn (1955)).

If the incident beam is composed of monoergic gamma rays, electrons of several discrete energies will be emitted. There will be a monoergic beam of K-shell electrons of energy $E_\gamma - I_K$ and similarly L-shell electrons of energy $E_\gamma - I_L$ and so on. If a thin layer of matter is placed in front of a gamma source, these photoelectrons will emerge from the foil with their initial momentum (and energy). The momenta of such electrons can then be measured with a beta-ray spectrometer. Once the photo-electron energies are known, the gamma-ray energy can be calculated. This process, known as external conversion is one of the most accurate methods of determining gamma-ray energy.

(ii) The Compton Effect

Compton (1922) was the first to explain the interaction of gamma rays with free or loosely bound electrons. The incident photon with initial energy E_γ is scattered by an electron and moves off at an angle ϕ to the incident direction with energy E_γ^1. The electron moves off at an angle Θ with energy E_e. By applying the relativistic laws for the conservation of momentum and energy, the following expression for E_γ^1 and E_e are obtained.

$$E_\gamma^1 = \frac{E_\gamma}{1 + r(1 - \cos\phi)}$$

$$E_e = \frac{2M_oC^2\, r^2 \cos^2\Theta}{1 + 2r + r^2 \sin^2\Theta} \qquad \text{where } r = \frac{E_\gamma}{M_oC^2}$$

The result is a continuous spectrum of electrons of energy from 0 to E_{mx}.

$$E_{mx} = \frac{2E_\gamma r}{1 + 2r}$$

Since no electrons of discrete energy are emitted, compton-scattered electrons are of limited use in determining gamma-ray energy. Compton scattering becomes more important as E_γ increases. This effect provides an unavoidable background which limits the sensitivity of the external conversion method in the present experiments.

(iii) Pair Production

A gamma ray of energy greater than 1.022 Mev ($2M_oC^2$), under the influence of a nucleus of high Z, may be annihilated, giving rise to an electron-positron pair. The energy of the gamma ray in excess of $2\,M_oC^2$ (the rest mass energy of the two particles created) is shared between the electron and the positron. The positron in general gets slightly more

energy because of the coulomb repulsion by the nucleus. The probability of pair production varies as the square of the atomic number of the radiated material and increases with energy. It plays no role in the experiments described in this thesis.

CHAPTER II. EXPERIMENTAL APPARATUS AND TECHNIQUES

(A) The Beta-Ray Spectrometer

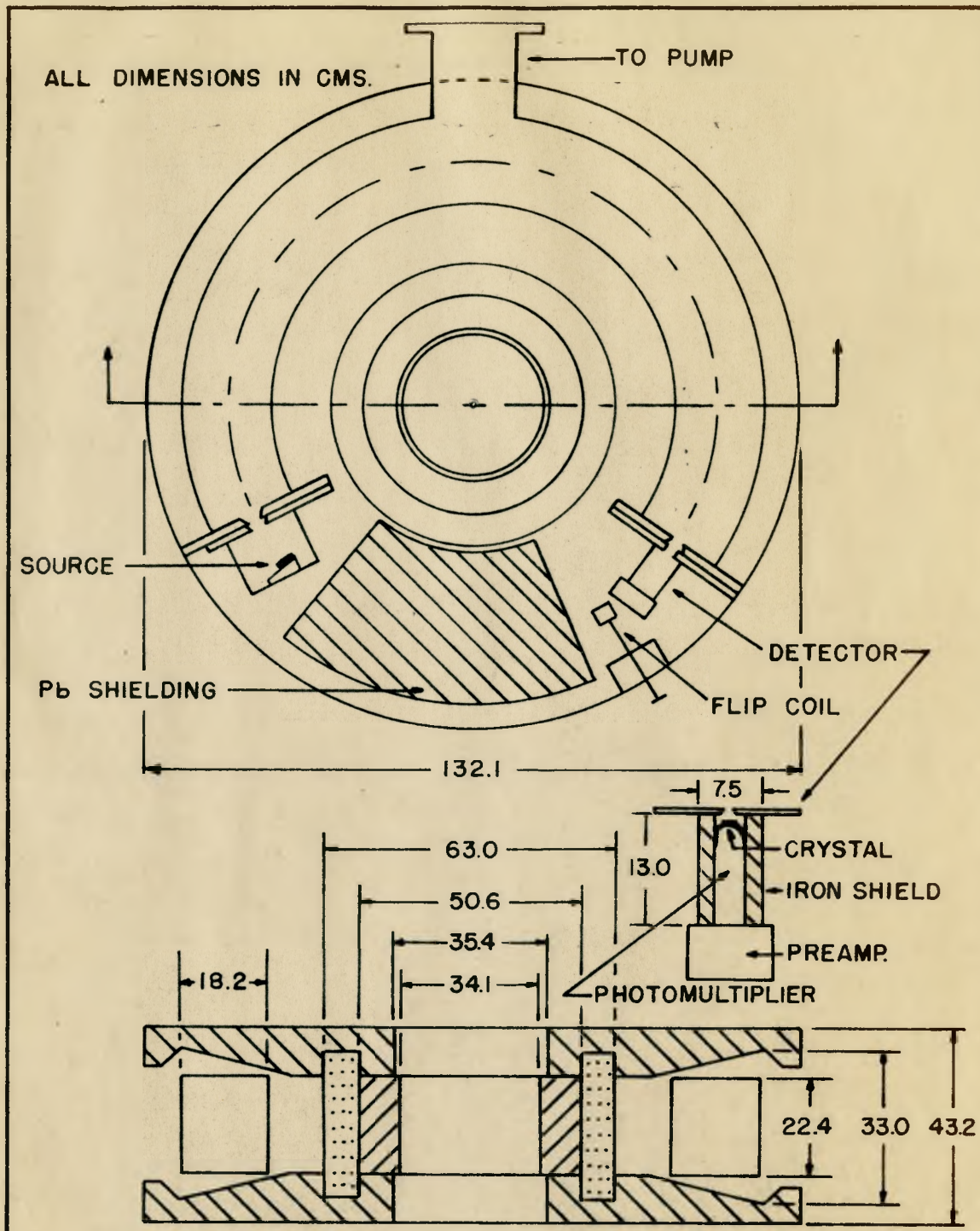
An electron with momentum p moving perpendicular to a magnetic field B will experience a force perpendicular to both B and p and will move in a circle of radius ρ given by

$$BeV = mV^2/\rho \qquad \text{or} \quad p = mV = B\rho e$$

where m is the relativistic mass and e, the electronic charge. In a uniform field, focusing in a plane perpendicular to B will occur at 180°. Seigbahn and Svartholm (1946) found that by careful shaping of the magnetic field, two-dimensional space focusing could be obtained at $\pi\sqrt{2}$ or 255.56°.

The spectrometer used in these experiments is a double-focusing instrument. Its construction and operation is described by Johns et al. (1953) and recent modifications by Artna (1961). The structure and dimensions of this instrument are shown in Figure 1. The magnet pole faces are of Armco iron with the magnet coil consisting of 10,000 turns of No. 18 formex wire wound in 8 pi's. The magnetic field is measured by means of a flip coil and a Leeds and Northrup type R galvanometer.

The source holder and detector are attached to sliding brass plates and can be removed from the vacuum chamber. The detector assembly consists of an anthracene crystal and a 9524S EMI cossor photomultiplier. In these



HIGH RESOLUTION BETA-RAY SPECTROMETER

FIGURE 1

experiments, the variable baffles were left open and the detector slits set at 4 mm. to give an instrumental resolution of about 0.6%.

(B) Methods of Source Preparation

This thesis is concerned with the preparation of beta sources and of antimony radiators. Radiators, the source of electrons in external conversion, are much thicker than beta sources but many of the same techniques can be applied to the preparation of both. In this section, methods of preparing thin foils will be discussed briefly. Evaporation (used in the preparation of antimony radiators) and ion ejection (used to prepare erbium beta sources) will be described in more detail.

For studying internal conversion and beta spectra, the ideal source should be a monatomic layer of active material on a monatomic layer of electrically conducting backing material. Although in practice neither of these can be realized, one must work towards these limits. The backing material should also be of low atomic number to reduce back-scattering. The backing material used for beta sources was 1/4-mil mylar aluminized on one side. The mylar provides a strong backing which is resistant to acid and alkali and the aluminum makes it electrically conducting. The shape of the source required for the beta-ray spectrometer is 0.5 cm. x 2.5 cm. for normal use - narrower if particularly high resolution is desired. Radiators were made larger (0.8 cm. x 3.0 cm.). A general discussion of source preparation is given by Dodson et al. (1952) and Parker et al. (1960).

(i) Electro-Deposition

Most of the information relative to the preparation of thin sources by this method is derived from industrial application. However, some industrial techniques are not applicable for trace amounts. Parker et al. (1960) studied electro-deposition using 0.1 N HCl or, in some cases, 0.1 N

NH_4OH as the deposition medium. Using electrodes of 5 mm. diameter and a deposition current of 2.0 ma/mm^2 for a period of one hour, the yield varied from 1 to 80%.

The apparatus for electro-deposition must be kept scrupulously clean and all chemicals used must be very pure. The disadvantages of this process are: 1) Because the backing material must form one of the electrodes, the choice of backing is very limited. 2) Some elements tend to adhere to the walls of the container. This effect appears to be less if the container is constructed of lucite.

(ii) Cathode Sputtering

This is one of the oldest techniques of source preparation but is little used now. The procedure used by Novakov and Mladjenović (1956) is as follows: The sample to be deposited is placed on a polished aluminum cathode and the source backing is positioned between the two electrodes about 8 mm. from the cathode. It is contained within a glass cylinder which is evacuated to a pressure of less than 10^{-2} mm. of Hg. With a voltage of 1000 volts and a current of 30 ma, an iridium source strong enough for use in a permanent magnet spectrometer was prepared in two hours. This method has been found very useful when the source material has a high melting point (e.g. osmium, iridium, lead, rubidium) and vacuum deposition is difficult.

(iii) Evaporation of Droplets

The active material is dissolved and drops of the active solution are placed on the source backing with a pipette and allowed to dry. By this method, all the activity can be placed on the backing so that a minimum of source material is required. This method was used previously in

this laboratory. However, the sources obtained were not homogeneous and showed source thickness effects for electrons of energy less than 200 kev.

(iv) Zapon Spreading Technique

To prepare sources by this method, a solution of the active material in the nitrate form is mixed with a dilute solution of zapon laquer in alcohol, acetone or zapon thinner. This is painted on the backing material, dried and ignited to remove organic material and convert the nitrate to an oxide. Following the directions of Dodson et al. (1952), uranium foils have been regularly prepared in this laboratory over the last seven years for use as radiators in external conversion. By repeating the procedure many times, quite thick radiators of good uniformity can be obtained. These foils were estimated to contain 79% uranium, 16% oxygen and 5% carbon.

(v) Electro-Phoretic

The material to be deposited must be in a fine powder form so as to form a stable suspension in alcohol. This suspension is placed in a metal cylinder about 10 mm. in diameter with the backing material along its axis. A potential of 300 to 800 volts is applied between the backing material and the cylinder - the polarity depends on the material to be deposited. The charging of the particles can be enhanced by the addition of a minute quantity of HCl or 0.1 mg. of tannic acid. Parker et al. (1960) found this method particularly good for the preparation of sources of the type used in a permanent magnet spectrometer. The disadvantages of this method are: 1) The active material must form a stable suspension in a non-conducting medium. 2) A lot of material is required to make a satisfactory suspension.

(vi) Vacuum Deposition

(a) Introduction

The main advantage of vacuum deposition over electro-plating is that it allows a wider choice of backing material. However, if care is not taken, the spread of contamination outside the apparatus can be very rapid. Two means are used to prevent the spread of contamination. The vapour may be collimated so that it is confined within a small solid angle or disposable shielding may be used.

Parker (1959) describes an apparatus designed to provide easy and rapid loading of the active material and sufficient collimation of the vapour to prevent contamination. The active material is placed in a crucible constructed of tantalum, molybdenum, iron or aluminum with a "chimney" 20 mm. long and 1 mm. in diameter. Heating is by radiation. By other techniques described in the literature the sample is placed directly on the heating filament (e.g., Barr and Blackburn (1959)).

(b) The Preparation of Antimony Radiators

The author used vacuum deposition in the preparation of antimony radiators. Because the apparatus was not used to deposit active material, no shielding or collimation of the vapour was necessary and therefore, the construction of the apparatus was very simple. The vacuum chamber consists of a bell jar placed on a metal plate which has connections for a diffusion pump and a voltage supply. When a partial vacuum is obtained an O-ring is placed around the base of the bell jar to improve the seal. The chamber is evacuated by means of a water-cooled, oil vapour, diffusion pump backed by a "Duo-Seal" vacuum pump. A water-cooled baffle-valve with an outlet to the backing pump is connected between the chamber and the diffusion

pump so that air can be let into the chamber and the backing pump without waiting for the diffusion pump to cool down.

The filament is connected between two brass pins placed 4.5 cm. apart. The power supply shown in Figure 2 provides a pulsed output. It was found that with a pulsed power supply, higher temperatures can be obtained without melting the filament. The time constants of the circuit are variable so that the time the current is on can be set anywhere between 0.8 and 5.8 seconds. The "off" time can be varied from less than 0.2 to 2.4 seconds. The output transformer is tapped at four points to give a maximum open circuit voltage of 30, 33.3, 36.6 or 40 volts.

The aim of these experiments was to make radiators with a lower binding energy than gold and still a reasonable photoelectric cross section. The first attempts were made with tin, using tungsten ribbon as a filament. However, the tin did not wet the filament sufficiently to obtain satisfactory evaporation. Good evaporation was obtained using antimony. The filament was a strip (0.7 x 4.3 cm.) of advance metal (a nickel and copper alloy) cut from a sheet 0.005 inches thick. The antimony, in powder form, was placed along the full length of the filament to make a radiator 0.8 x 3.0 cm. The backing material used was aluminum foil (about 5 mg./cm.^{2} thick) which was located about 2 cm. above the filament. Good evaporation was obtained with a current of 18 amperes at which point the filament was just beginning to show colour.

After evaporation, the foil was weighed and the weight of the aluminum subtracted to find the density of the antimony film. The thickness was checked by gamma-ray intensity measurement. Films as thick as 3 mg./cm.^{2} were prepared. However, films of thickness greater than

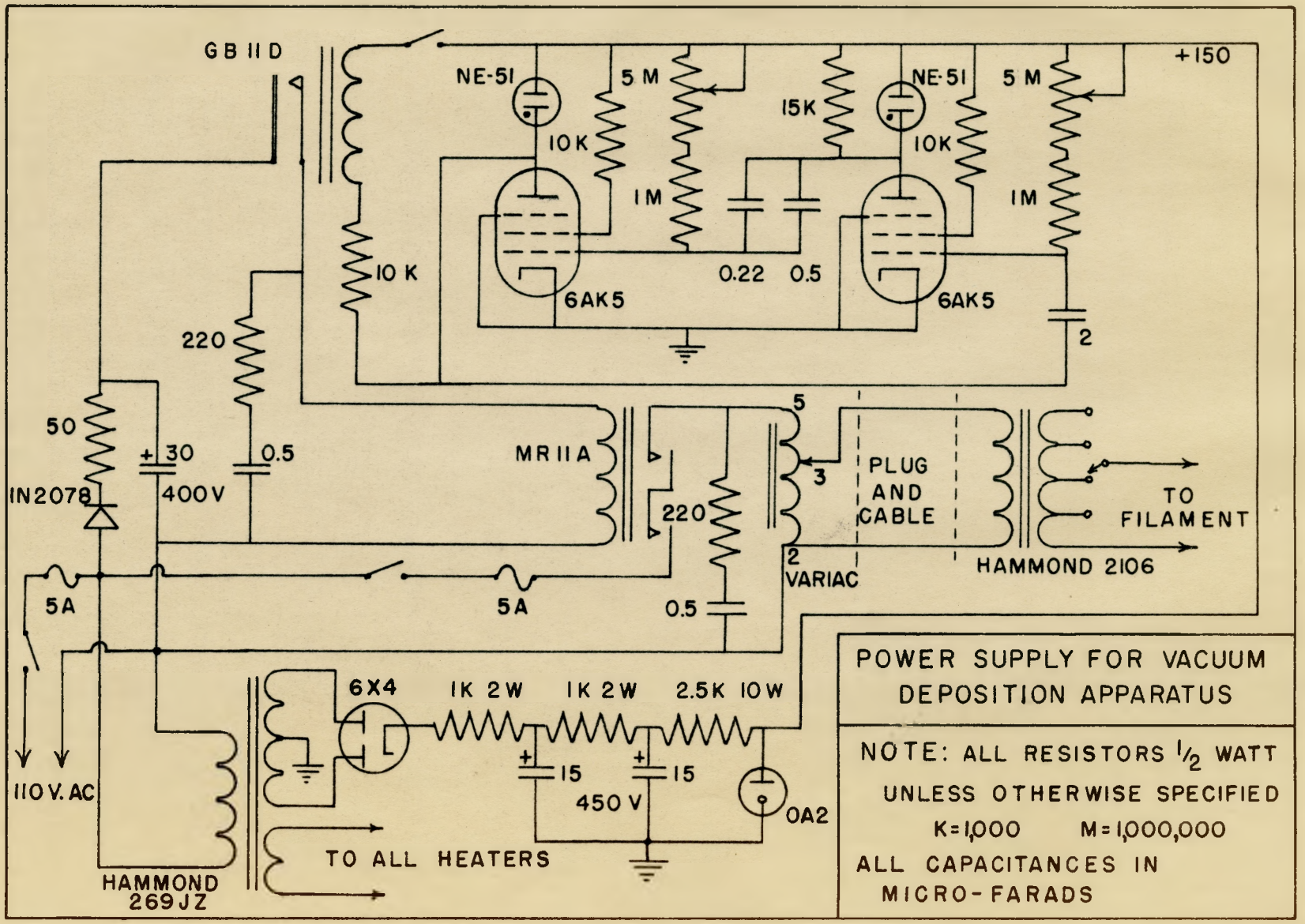

GB 11 D
NE-51
5 M
10K
1M
15K
NE-51
10K
5 M
1M
+150
10 K
220
6AK5
0.22
0.5
6AK5
2
50
± 30
400V
0.5
IN2078
MR 11A
220
5
3
2
PLUG AND CABLE
TO FILAMENT
VARIAC
HAMMOND 2106
5A
5A
0.5
6X4
1K 2W
1K 2W
2.5K 10W
15
15
450 V
0A2
110 V. AC
TO ALL HEATERS
HAMMOND 269JZ
POWER SUPPLY FOR VACUUM DEPOSITION APPARATUS
NOTE: ALL RESISTORS 1/2 WATT
UNLESS OTHERWISE SPECIFIED
K=1,000 M=1,000,000
ALL CAPACITANCES IN MICRO-FARADS

FIGURE 2

1 mg./cm.^{2} were of little use in the low energy region. The mounting of these radiators and their application to gamma-ray intensity measurements will be discussed in Chapter III.

(vii) Ion Ejection

(a) Introduction

In the ion ejection method, developed by Carswell and Milsted (1957), a capillary tube is drawn out to make a fine jet so that, under normal conditions, no liquid can escape. A fine wire is inserted in the capillary to within a few millimeters of the tip and a potential of from 3 to 10 kilovolts applied between this wire and the backing material which is placed about 1 cm. from the end of the pipette. The pipette must be filled with a non-conducting solution of the active material and the backing must be electrically conducting. When the voltage is applied, the charged particles and the solvent are ejected together in a fine mist. The solvent evaporates and the active material is collected by the backing. Such sources are much more uniform than those prepared by the droplet evaporation technique.

(b) The Preparation of Erbium Sources

It was decided to prepare the erbium beta sources by this method because it required a minimum of equipment. Also, the entire preparation could be carried out in the dry-box which eliminated the danger of contamination.

The pipettes were made by drawing out 7 mm. capillary tubing and inserting a fine copper wire. After the pipette was filled, it was clamped in a horizontal position. The backing material was glued on the source holder which fitted in the spectrometer. The source area was defined by

pasting on the source holder a piece of waxed paper in which there was a hole the shape and size of the desired source. The source holder slid into position against a metal plate which was attached to a piece of brass. This fitted into a "track" (also of brass) so that the backing could be moved back and forth in front of the pipette to make a strip source. All this equipment was placed in the dry-box.

The high voltage was brought into the dry-box by means of a heavy-duty co-axial cable through the dry-box wall. The anode lead was clipped to the wire into the pipette and the ground lead to the source backing.

To prepare erbium beta sources, erbium oxide (Er_2O_3) sealed in a quartz capsule was irradiated in the McMaster Reactor. In the dry-box, the quartz capsule was broken under concentrated nitric acid and the contents dissolved therein. The solution was then placed under the heat lamp and evaporated to dryness. To be sure all the acid was removed, the erbium nitrate was dissolved in water and again evaporated just to dryness. Then acetone was added and the pipette was filled with the resulting "solution". A potential difference of about 3000 volts was applied.

The low-energy part of the erbium-171 spectrum studied using a source prepared by this method is shown in Figure 3. This Figure shows the internal conversion of gamma rays in Tm^{171}. Although the energy of the electrons detected is between 50 and 65 kev, the resolution is good and the low-energy tail is very small. Also it can be seen that the shape of the peak is regular. This shows that the source was a thin, even layer of active material.

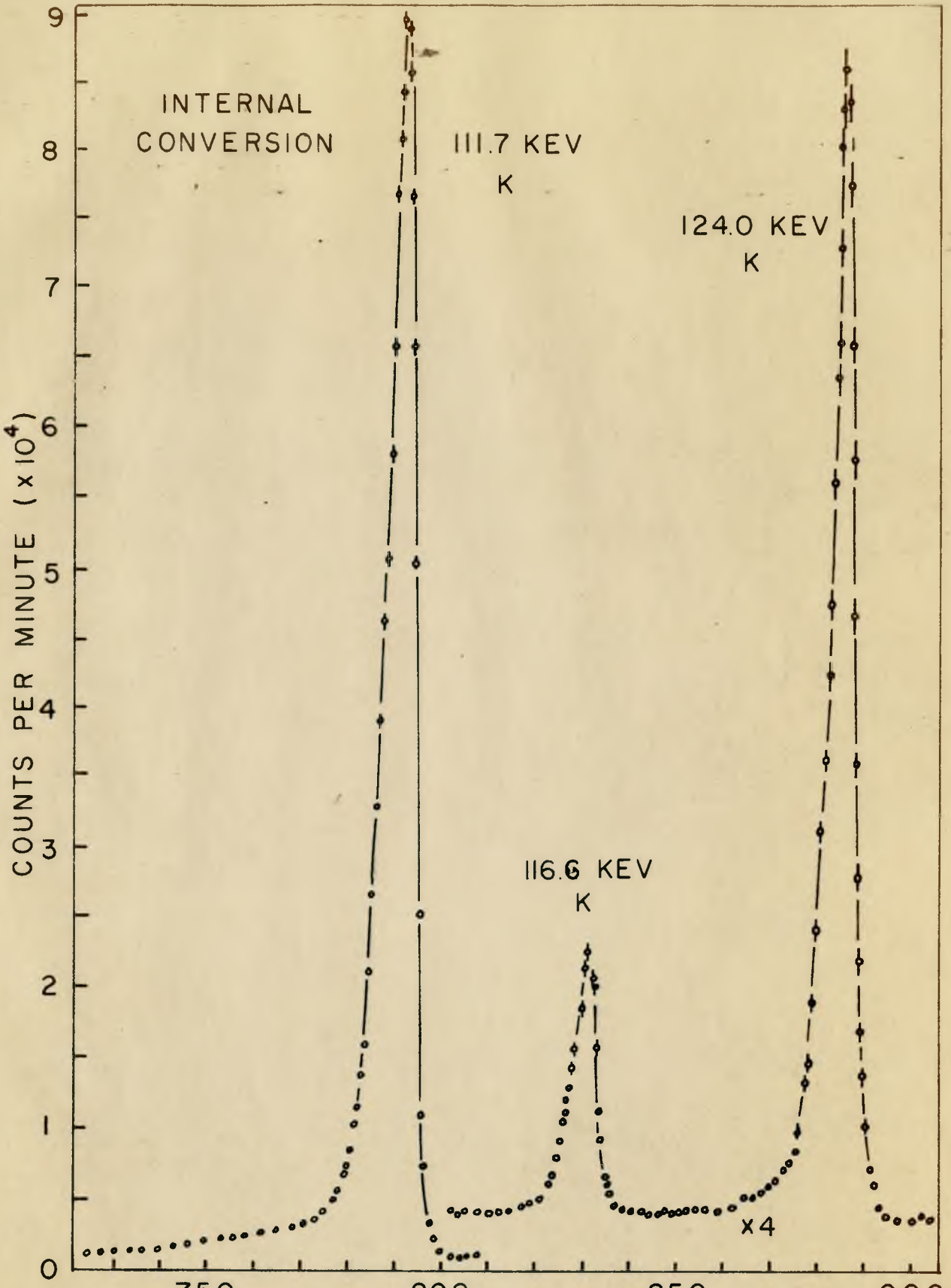

INTERNAL
CONVERSION
111.7 KEV
K
124.0 KEV
K
116.6 KEV
K
X4
COUNTS PER MINUTE (x 10⁴)
0
1
2
3
4
5
6
7
8
9
750
800
850
900
Bρe (GAUSS-CM)

FIGURE 3

It seems reasonable that this method could be applied to all the rare earths since the chemistry of all members of this series is very similar. Instead of acetone, carbon tetrachloride or any organic liquid which evaporates rapidly can be used.

CHAPTER III. THE DETERMINATION OF GAMMA-RAY INTENSITIES

Introduction

The determination of gamma-ray intensities from a study of the external conversion spectrum has been the subject of some study in this laboratory. The relationship between the peak height or area and the gamma-ray intensity depends on the photoelectric cross section, the mass of the radiator, the degree of multiple scattering of the photoelectrons in the radiator, and various geometric factors such as the source-radiator geometry and the spectrometer transmission. Since for all the radiators used, a good deal of multiple scattering occurs, one expects the photoelectrons to be emitted essentially isotropically and with a spread in energy downward from $(h\nu - E_K)$ (E_K is the K-shell binding energy, $h\nu$, the photon energy). The spread in energy depends on the electron energy as well as the thickness and composition of the radiator.

There are two approaches to the problem of determining gamma-ray intensities by means of a beta-ray spectrometer. That suggested by Deutsch (1944) involves setting up a relationship between the peak height and the photon intensity. This method, which has been used previously in this laboratory, can only be used to find relative intensities since the instrumental transmission and the source-radiator geometry do not enter into the formula but are assumed constant. A method of measuring absolute gamma intensities is described by Hultberg (1959). In these calculations,

the source-radiator geometry must be known and any change of this geometry involves cumbersome calculations which require the use of a computer. Unless one is willing to repeat such a calculation for every source, all sources must have known and reproducible geometric dimensions.

All the gamma sources used in these experiments were sealed in quartz so that they could be re-irradiated and since the amount of material irradiated depended upon the neutron capture cross section and the half-life, to maintain constant source-radiator geometry would have been extremely difficult. Therefore, it was decided to continue using the method proposed by Deutsch.

Artna (1961) made a careful study of gamma-ray intensities using gold and uranium radiators. Using gamma rays of known relative intensity, a set of semi-empirical curves were drawn for the gold and uranium radiators used in the study of erbium. However, these curves were not well defined for gamma-ray energies less than 200 kev. Moreover, the presence of gold Auger electrons makes it difficult to measure the peak heights produced in gold radiators between 50 and 65 kev. It was decided that some better means was needed to measure the intensities of very low energy gamma rays (80 to 200 kev). For this purpose, antimony radiators were prepared as described in Chapter II. Antimony has a K-shell binding energy of 30.5 kev. This means that the K-shell photoelectrons from a given gamma ray have an energy about 50 kev greater than their counterparts from gold.

In this Chapter, the theoretical expression relating peak height to gamma-ray intensity will be discussed and the experimental results with antimony radiators will be presented.

(A) A Theoretical Expression for Gamma-Ray Intensities

When a beam of gamma rays passes through a radiator, photoelectrons will be created throughout its entire volume. The number produced in a radiator of thickness t will be proportional to $I_\gamma \tau t$ where I_γ is the intensity of gamma rays, τ the photoelectric cross section, and they will have a spread in energy (or momentum). This spread in momentum, expressed in gauss-cm., we shall designate by $\Delta B\rho$.

For a given magnetic field, in the spectrometer, electrons of momentum from p to p + Δp will be detected. Δp is a function of p given by $\Delta p = Rp$, where R is the instrumental resolution which is constant for a given source-baffle-detector geometry.

Now if $Rp \gg \Delta B\rho$, then all the photoelectrons will be detected at the same time and the peak height will be proportional to the number of photoelectrons created. In this case the peak height is given by

$$n = k I_\gamma \tau t \qquad (3.1)$$

where k is a constant of the spectrometer and the source radiator geometry.

If $Rp \ll \Delta B\rho$, then only a small fraction $Rp/\Delta B\rho$ of the photoelectrons will be detected at one time. Then

$$n = k I_\gamma \tau t\left(\frac{Rp}{\Delta B\rho}\right) \qquad (3.2)$$

If we define the stopping power I of a material by $I = dB\rho/dt$, then $\Delta B\rho = I.t.$ For convenience a factor C will be defined by $C \equiv I\beta^3$. Substituting for $\Delta B\rho$ and I in equation (3.2), we obtain

$$n = k I_\gamma \tau(Rp\beta^3/C) \qquad (3.3)$$

Since the general case is intermediate between the two extreme cases described above, Deutsch suggested the following approximation for the general case:

$$n = kI_\gamma \tau t \left[1 + \left(\frac{Ct}{R_p \beta^3} \right)^2 \right]^{-1/2} \qquad (3.4)$$

Rearranging the above equation leads to the expression

$$I_\gamma = \frac{Kn}{\tau_p \beta^3} \left[C^2 + \left(\frac{R_p \beta^3}{t} \right)^2 \right]^{1/2} \qquad (3.5)$$

where K = 1/kR which is constant if the source-radiator geometry and the baffle settings are not changed. Therefore K does not enter into the calculations of relative intensities.

White and Millington (1928) showed that C was approximately constant for $B\rho \geq 1400$ gauss-cm. Deutsch, in his calculations, took C as constant which is a valid assumption in the region where $\frac{R_p \beta^3}{t} \gg C$. However, at lower energies, the variation of C with electron momentum and radiator thickness must be taken into account. Chen and Warshaw (1951) made a careful study of the stopping power of various materials for electrons. In their paper they give the most probable energy loss T_o of electrons in traversing a thickness x of matter, calculated from the Landau theory as

$$T_o = \frac{x}{\beta^2} \ln \frac{2x}{(1 - \beta^2) E_i^2 \exp (\beta^2 - 0.37)} \qquad (3.6)$$

Energy is in units of mc^2 and distances are measured in units of $(2\pi r_o^2 n)^{-1}$ (r_o is the classical radius of the electron; $n = NdZ/A$ is the density of electrons in the stopping material of density d, atomic number Z, and atomic weight A; N is Avagadro's number). E_i is the mean ionization potential of the stopping material. We can now calculate the most probable momentum loss $\Delta B\rho$ corresponding to T_o, and the ratio $\Delta B\rho/t$ corresponding to T_o/x. Now

$$C = I\beta^3 = \frac{\Delta B\rho}{t} \beta^3 \qquad (3.7)$$

If we substitute in equation (3.7) the value of $\Delta B\rho/t$, the following equation for C is obtained

$$C = 1.18 \frac{Z}{A}\left[\log t + \log\left(\frac{Z}{A}\right) - 2 \log E_i - \log (1 - \beta^2) - 0.434\ \beta^2 + 8.35\right] \tag{3.8}$$

where E_i is in electron volts and t is in mg./cm.^{2}. To find E_i, the value of E_i/Z for tin given by Bakker and Segrè (1951) was used. This gave a value of E_i = 484 ev. for antimony.

If the values of Z/A and E_i for antimony are substituted in equation (3.8) it becomes

$$C = .494\left[2.603 - \log (1 - \beta^2) - 0.434\ \beta^2 + \log t\right] \tag{3.9}$$

In calculating the value of τ for antimony it was assumed that the ratio of the K-shell to the total photoelectric cross section is constant. The value of τ for antimony was obtained by interpolating between the values for tin (Z = 50) and iodine (Z = 53) given by Siegbahn (1955).

Using the value of C obtained from equation (3.9), the theoretical values of $1/\tau p\beta^3$ and $\sqrt{C^2 + \left(\frac{Rp\beta^3}{t}\right)^2}$ were calculated for several values of $B\rho_e$ between 500 and 3000. These values were plotted on separate graphs and a smooth curve drawn through the points. Figure 5 shows the variation of $1/\tau p\beta^3$ with $B\rho$ for gold and antimony and the solid lines in Figures 6 and 7 show $\sqrt{C^2 + \left(\frac{Rp\beta^3}{t}\right)^2}$ for the antimony and gold radiators used in these experiments. The experimental test of this theory will be discussed later.

(B) <u>The Mounting of Antimony Radiators</u>

For external conversion, the radiator is mounted on a steel cylinder 0.8 mm. thick. This is placed inside the spectrometer vacuum

chamber and a vacuum seal is made by means of two O-rings around the cylinder above and below the radiator. The source of gamma rays, sealed in quartz, is glued to a brass plug which slides into the steel cylinder and is positioned so that the source is directly behind the radiator.

The steel cylinder produces a photoelectric peak as well as the radiator. Because of the thickness of the cylinder, this peak is very broad, rising very gradually on the low energy side but dropping abruptly on the high energy side. When a radiator is placed on the steel cylinder, these electrons in passing through the radiator will be retarded and the peak becomes rounded off. When gold and uranium radiators were used, the iron photo-peak presented no problem because the binding energy of iron (7.1 kev) is much less than that of gold (80.7 kev) or uranium (115.6 kev), and also the heavier radiators absorbed some of the electrons. However, when the thin antimony radiators were mounted in this manner, the photo-peak became troublesome. Since antimony has a binding energy only 23.4 kev higher than iron and since the photoelectrons from the iron were slightly retarded in passing through the radiator, the photo-peak from the antimony was just at the high energy edge of the photo-peak from iron. This made it very difficult to determine the peak height.

To overcome this problem, a sheet of aluminum about 60 mg./cm.^{2} thick was placed between the steel cylinder and the radiator. This is sufficient to stop 250 kev electrons (Siegbahn (1955) Chapter I). The effect of the aluminum sheet on the gamma-ray intensity is negligible - the intensity of 80 kev gamma rays in reduced by about 1%. Hence the peak height is not affected but the counting rate under the peak is much more regular and greatly reduced.

(C) To Find the Radiator Thickness

To find the gamma intensity, using equation (3.5), it is necessary to know the radiator thickness. An estimate of the thickness was made by weighing the radiator on an analytical balance to the nearest 0.1 mg. and subtracting the weight of the aluminum foil used as backing material. This method did not prove to be very reliable, both because the household aluminum foil used as backing material was not absolutely uniform, and because the density of the deposit tended to be less near the ends of the radiator. Although the thin portions were cut off after the foil was mounted for use, it was necessary to do the weighing before the ends were cut off. It was therefore felt that a better measure of the effective thickness could be made by comparing these foils with gold foils whose thickness could be calculated from the number of layers of gold leaf used in their manufacture.

By rearranging equation (3.4) the following expression for radiator thickness as a function of peak height is obtained.

$$t = \frac{n}{kI_\gamma \mathcal{T}} \left[1 + \left(\frac{Ct}{R_p \beta^3} \right)^2 \right]^{1/2}$$

The external conversion peak height of the 412 kev gamma ray in Au^{198} was measured using three gold and four antimony radiators. Since at this momentum, the term $\left(\frac{Ct}{R_p \beta^3} \right)^2$ was $\leqslant 0.06$ for the antimony radiators, it was not necessary to know C precisely. Thus a plot of

$$n/\mathcal{T} \left[1 + \left(\frac{Ct}{R_p \beta^3} \right)^2 \right]^{1/2}$$

against t is really a plot of $n/\mathcal{T}$ versus t. This graph may be expected to

be a straight line of slope 1 on a log-log plot. Figure 3A presents the graph for the 412 kev transition using three gold radiators of known thickness. It is seen that the straight line passes through all three points. The thicknesses of the antimony radiators were adjusted to fit on this line. As a check on the correctness of these thicknesses, the gold and antimony points were compared for the lower energy 308 kev transition of Er^{171}. A plot of these results is also shown in Figure 3A. The points fall nicely on the straight line when the antimony thickness derived from the 412 kev line are used. The thicknesses assigned in this manner to the antimony radiators were 0.44, 0.76, 1.00 and 1.85 mg./cm.^{2}.

To study the effect of radiator thickness on peak height and resolution at very low energies, the 80.6 kev gamma ray in Ho^{166} was examined with the four radiators. The peaks obtained with the three thinnest radiators are shown in Figure 4. It is seen that with increasing radiator thickness, the resolution becomes poorer, the peak height increases at first but after a certain thickness is reached it decreases. The thickest radiator (1.85 mg./cm.^{2}) showed a much poorer resolution and a lower peak height. No further experiments were done using this radiator, since in the energy range where it would give good peaks, its yield would have been much smaller than that obtainable from gold.

(D) The Experimental Method

It had been found (Artna (1961)) that equation (3.5) is quite reliable for $B\rho_e > 1500$ gauss-cm. if the radiator is very thin (< 1 mg./cm.^{2}). For $B\rho_e < 1500$ gauss-cm. and thicker radiators, the experimental points do not fit the theoretical curve and the shape of the curve was not known. The present experiments were planned to yield more reliable curves in this region.

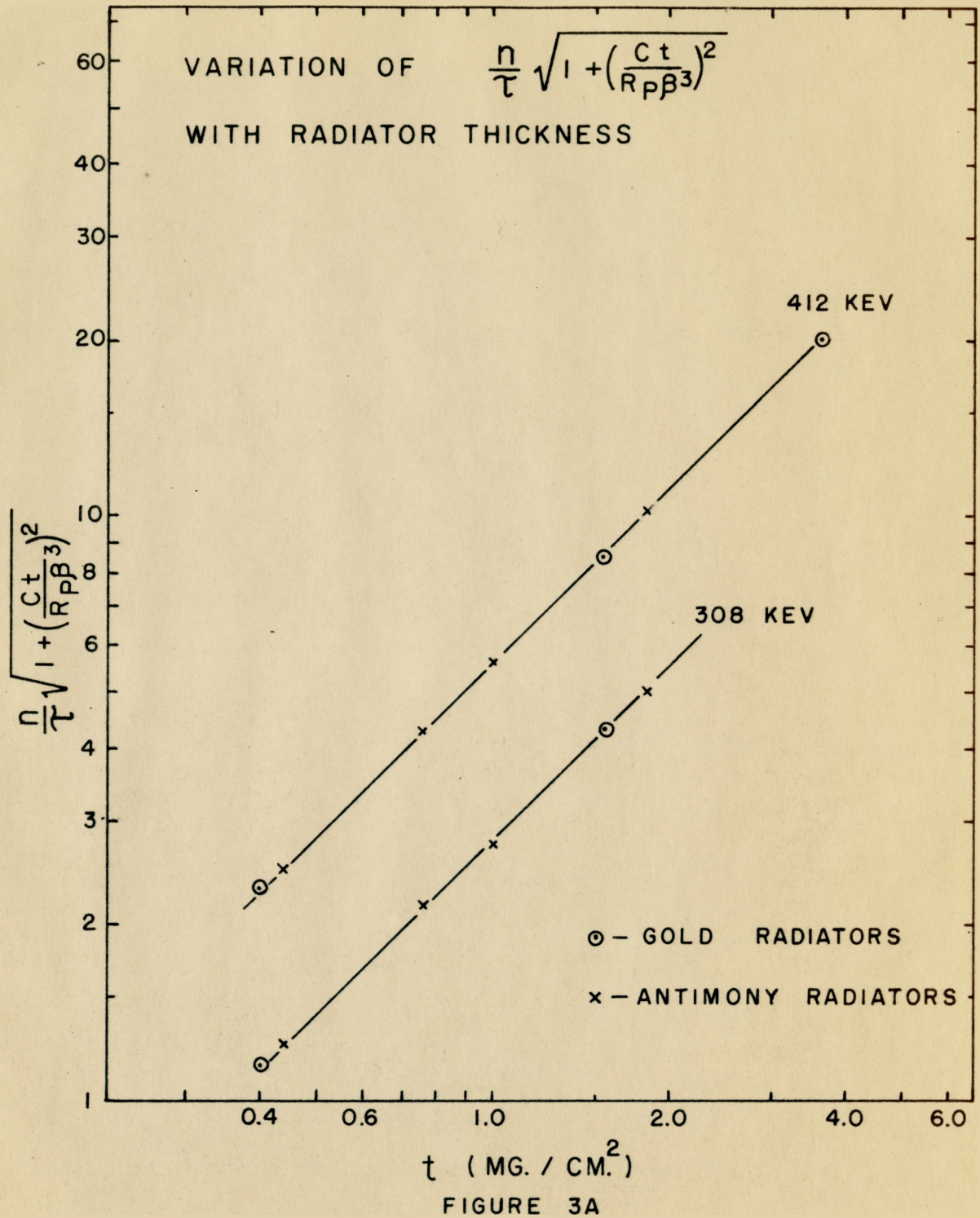

VARIATION OF $\frac{n}{\tau}\sqrt{1+\left(\frac{Ct}{R_P\beta^3}\right)^2}$
WITH RADIATOR THICKNESS
412 KEV
308 KEV
⊙ – GOLD RADIATORS
× – ANTIMONY RADIATORS
$\frac{n}{\tau}\sqrt{1+\left(\frac{Ct}{R_P\beta^3}\right)^2}$
60
40
30
20
10
8
6
4
3
2
1
0.4
0.6
1.0
2.0
4.0
6.0
t (MG. / CM.^{2})

FIGURE 3A

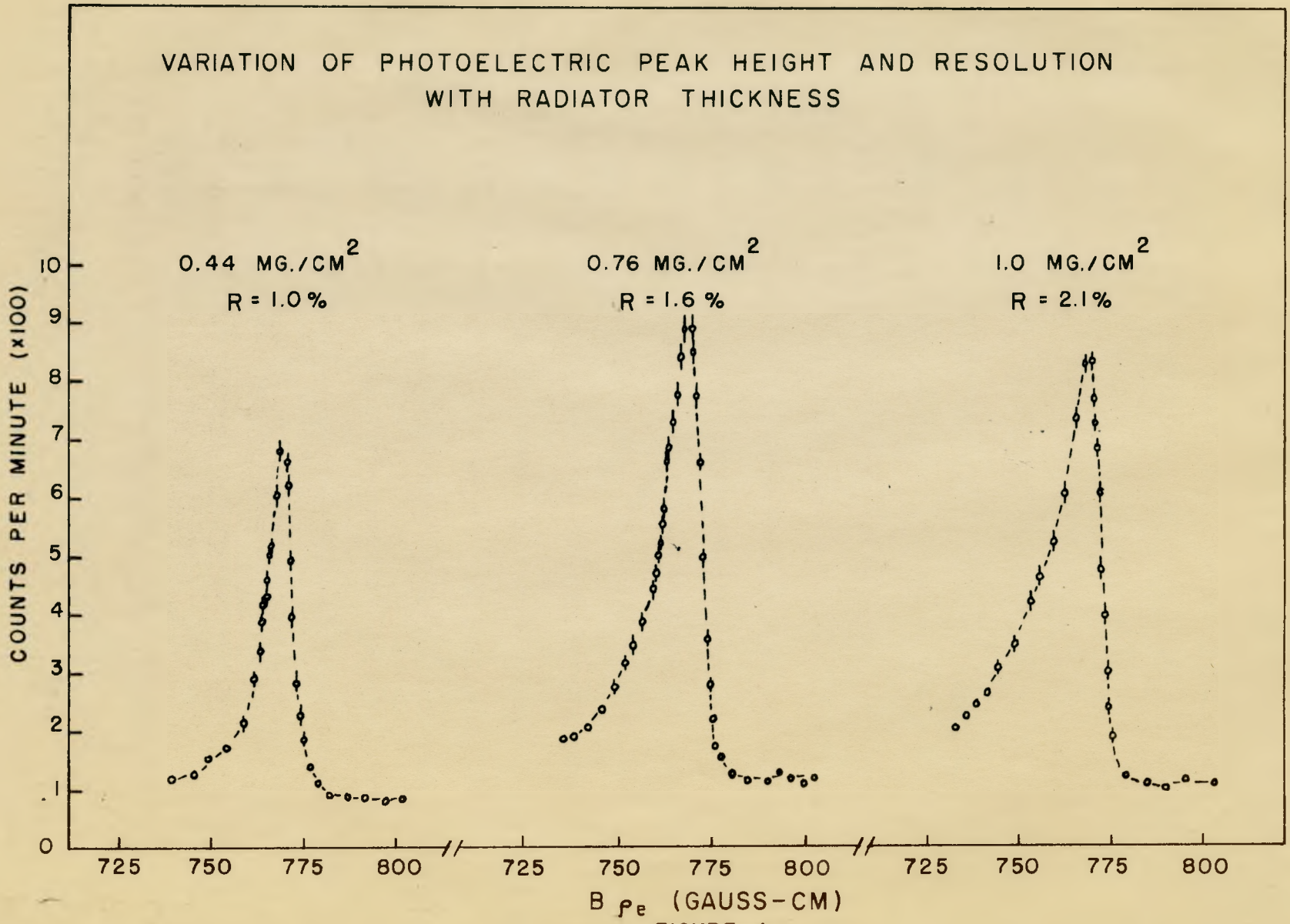

VARIATION OF PHOTOELECTRIC PEAK HEIGHT AND RESOLUTION
WITH RADIATOR THICKNESS
0.44 MG./CM2
R = 1.0%
0.76 MG./CM2
R = 1.6 %
1.0 MG./CM2
R = 2.1%
COUNTS PER MINUTE (x100)
0
1
2
3
4
5
6
7
8
9
10
725
750
775
800
B ρe (GAUSS-CM)

FIGURE 4

To check this theory, it is necessary to have gamma rays of known relative intensity. These are not easy to find but the cascading E2 transitions within a rotational band in an even-even nucleus offer the best choices. Miss Artna used the 885 and 1119 kev pair in Sc^{46}, the 556 and 772 kev pair in In^{114} and the 216 and 332 kev pair in Hf^{180m}. The Hf^{180m} has a third member in the band of energy 93 kev which was useless in her work but which provided an excellent standard for the antimony radiators. In fact the Hf^{180m} triplet provides three gamma rays of known relative intensity covering the entire region of interest in this work. As a secondary set of known lines the gamma rays of energy 116, 124 and 308 kev in the decay of Er^{171} were used since their relative intensity had been carefully determined by Miss Artna through direct measurement and the intensity balance of the Er^{171} decay scheme.

Before describing the experiments carried out with antimony radiators, it should be mentioned that equation (3.5) gives the intensity of gamma rays reaching the radiator. To find the relative transition intensities, two factors must be taken into consideration; the absorption of gamma rays in the steel cylinder and internal conversion. The absorption in the steel cylinder (of thickness 0.63 gm/cm.^{2}) has been calculated using the total mass absorption coefficient for iron given by Siegbahn (1955). The total internal conversion coefficient is more difficult to obtain. In the case of Hf^{180m}, the transitions studied were pure E2 and the theoretical values of the internal conversion coefficients calculated by Sliv (1956) were used.

(E) Experimental Results

The experimental results obtained for antimony are listed in Table II. The first two columns give the sources and gamma-ray energy used. The column entitled "Relative Photon Intensity" gives the relative intensity of gamma-rays reaching the radiator, making allowance for the internal conversion and the absorption in the steel cylinder. The last three columns give the measured peak heights. Since Hf^{180m} has only a 5.5-hr. half-life, the data for each radiator were taken with a different source. Thus the relative peak heights between radiators for the hafnium gamma-rays have no significance.

The peak heights of the three transitions in Hf^{180m} were measured in each of the three radiators. The intensity was found using the peak height of the 332 kev transition and the theoretical value of $\sqrt{C^2 + (R\rho\beta^3/t)^2}$ and, assuming this value, the factor $\sqrt{C^2 + (R\rho\beta^3/t)^2}$ was found for the other transitions. These results showed that the curves turned up at low energies but they did not determine the depth of the valley near $B\rho_e$ = 1300 gauss-cm. As can be seen from Figure 6, the points corresponding to the 216 kev transition lie very nearly on the theoretical curve but the 93 kev transition gave points on the graph roughly four times the theoretical values. To determine the nature of the curve between these two points the 116, 124 and 308 kev transitions in Tm^{171} were studied with the thinnest radiator. (Again the intensity was calculated using the peak height of the highest energy transition.) A smooth curve was then drawn through these points. This experiment might have been repeated for each of the other radiators. Instead, it was convenient to compare the behaviour of the three radiators in the momentum range below $B\rho_e$ = 1250 gauss-cm. using gamma-rays from longer lived nuclides (4-day Re^{186}

TABLE II

Data on Intensity Measurements

Source	Gamma Energy (kev)	Relative Transition Intensity	Relative Photon Intensity	Peak Height		
				0.44 mg/cm^2	0.76 mg/cm^2	1.0 mg/cm^2
Hf^{180m}	93.3	100	15.5	50 ± 7	61 ± 7	49 ± 6
	216	100	85.2	155 ± 9	215 ± 11	190 ± 14
	332	100	100	58 ± 7	80 ± 7	86 ± 7
Er^{171}	116		3.23	250 ± 11		
	124		12.7	990 ± 28		
	308		100	1585 ± 34		
Re^{186}	137			212 ± 11	340 ± 22	406 ± 15
Re^{188}	155			773 ± 18	1180 ± 21	1595 ± 24
Ho^{166}	80.6			652 ± 23	850 ± 29	795 ± 23

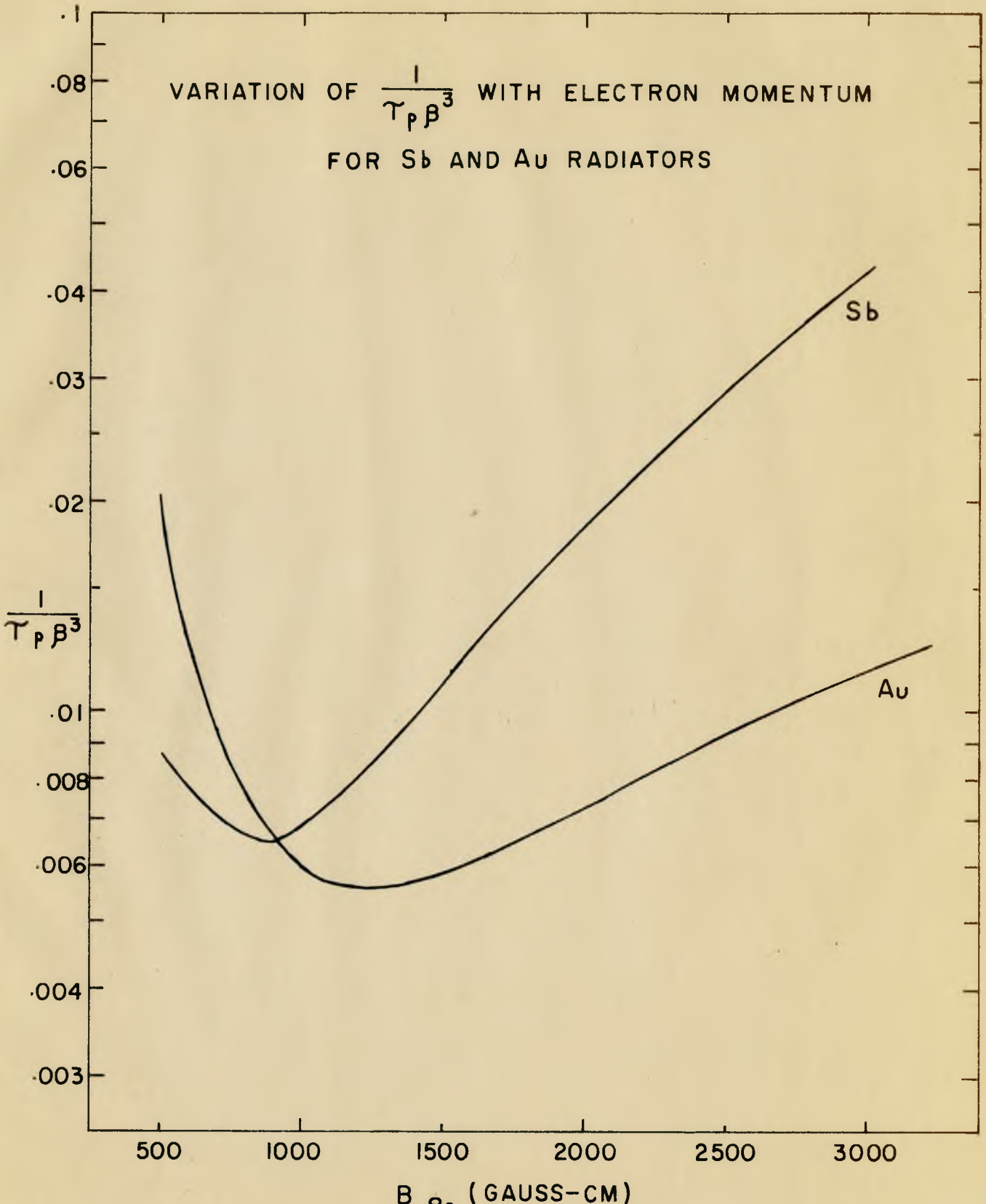

VARIATION OF $\frac{1}{\tau_p \beta^3}$ WITH ELECTRON MOMENTUM
FOR Sb AND Au RADIATORS
Sb
Au
$\frac{1}{\tau_p \beta^3}$
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
500
1000
1500
2000
2500
3000
B ρ_e (GAUSS-CM)

FIGURE 5

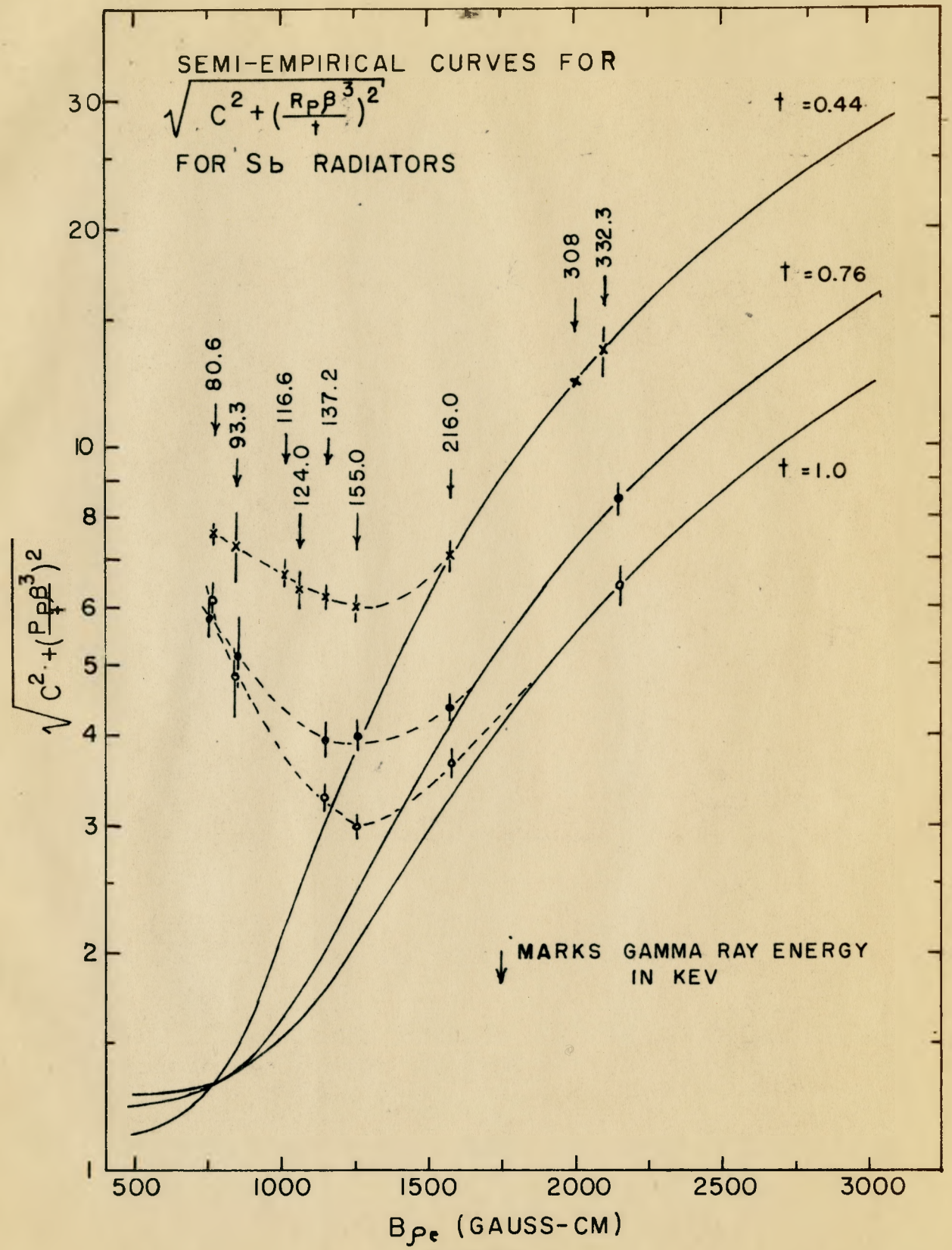

SEMI-EMPIRICAL CURVES FOR
$\sqrt{C^2+(\frac{R_p\beta^3}{t})^2}$
FOR Sb RADIATORS
t =0.44
t =0.76
t =1.0
80.6
93.3
116.6
124.0
137.2
155.0
216.0
308
332.3
MARKS GAMMA RAY ENERGY IN KEV
$\sqrt{C^2+(\frac{P_p\beta^3}{t})^2}$
$B_{\rho e}$ (GAUSS-CM)
30
20
10
8
6
5
4
3
2
1
500
1000
1500
2000
2500
3000

FIGURE 6

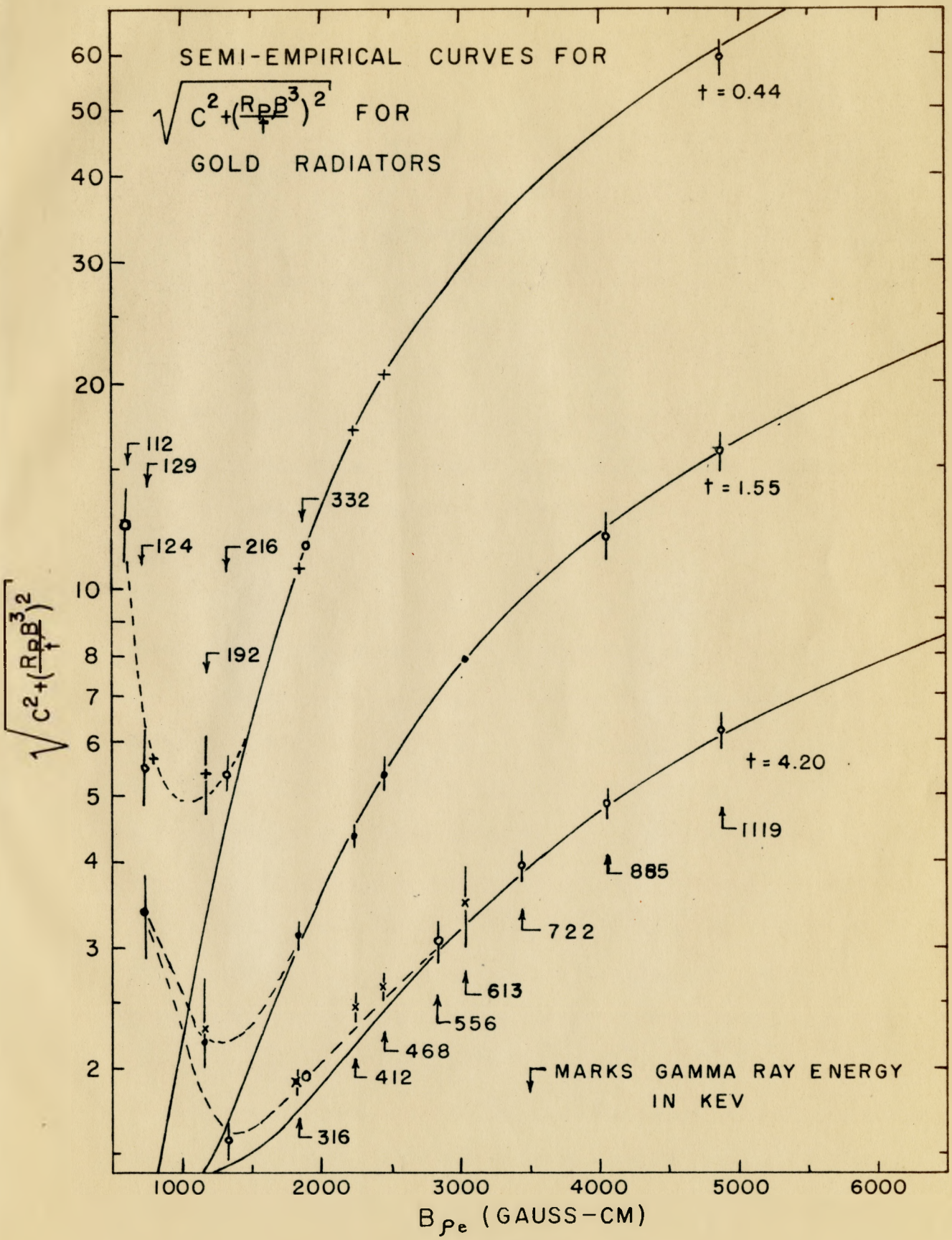

SEMI-EMPIRICAL CURVES FOR
$\sqrt{C^2+(\frac{R_p B^3}{t})^2}$ FOR
GOLD RADIATORS
t = 0.44
t = 1.55
t = 4.20
112
129
124
216
332
192
1119
885
722
613
556
468
412
316
MARKS GAMMA RAY ENERGY IN KEV
$\sqrt{C^2+(\frac{R_p B^3}{t})^2}$
$B_{\rho e}$ (GAUSS-CM)
60
50
40
30
20
10
8
7
6
5
4
3
2
1000
2000
3000
4000
5000
6000

FIGURE 7

18-hour Re^{188} and 27-hour Ho^{166}). In these measurements it was necessary to keep source-radiator and source-baffle-detector geometry constant. This was achieved by gluing the source to the brass plug, by mounting the radiators on identical steel cylinders, by making the three radiators the same size (0.8 x 3.0 cm.) and by keeping the baffles open and detector slits at 4 mm. in all measurements. Using the values of $\sqrt{C^2 + (Rp\beta^3/t)^2}$ given by the empirical curve drawn for the 0.44 mg./cm.^{2} radiator, the gamma-ray intensity was found and used in the calculation of the value of $\sqrt{C^2 + (Rp\beta^3/t)^2}$ for the other two radiators. The intercalibration points for the two thicker radiators showed good agreement with the Hf^{180m} points. Using the intercalibration points an empirical curve was drawn for these two radiators. The empirical results are shown by the dotted lines on Figure 6.

(F) A Comparison of the Results with Antimony and Gold Radiators

Comparing Figures 6 and 7, a number of similarities are observed. (1) In both cases the experimental points deviate from the theoretical curve at the low energy end. (2) This deviation begins at approximately the same $B\rho_e$ for gold and antimony radiators of the same thickness. (3) The deviation begins at a higher value of $B\rho_e$ for thicker radiators. (This is more marked in Figure 7 where the difference in thickness is greater.) (4) The curves show a similar but not identical shape. The factor $\sqrt{C^2 + (Rp\beta^3/t)^2}$ depends on the radiator material only through C. In the region where $Rp\beta^3/t \gg C$ the curves for gold and antimony become identical. However, in the lower energy region the difference becomes significant. For radiators of thickness 0.40 mg./cm.^{2} the curves for gold and antimony are identical for $B\rho_e > 1600$ but at lower energies they differ by about 25%.

In calculating the most probable energy loss by the photoelectrons by the Landau theory it is assumed that the electron is scattered many times before it reaches the surface of the radiator and that in each scattering process, the energy lost by the electron is small compared to its initial energy. In other words, it is assumed that before each collision the electron has its initial energy. This is not a valid assumption for electrons of about 100 kev and less. The resolution of the 80.6 kev line in antimony varies from 1 to 2% (Figure 4), although the instrumental resolution is 0.6%. This indicates that in the radiator of thickness 1.0 mg./cm.^{2}, a number of photoelectrons lost 5% or more of their initial energy. It seems reasonable that this effect will be more marked in the thicker radiators where the number of scatterings is greater.

The interaction of electrons of this energy is too complicated to deal with theoretically and therefore it is necessary to use empirical curves to relate peak height to gamma-ray intensity in this region.

SUMMARY

To measure relative gamma-ray intensities within a source, the peak heights are measured and decay corrected to a common time. The peak heights are multiplied by the product of the factors $1/\tau p\beta^3$ and $\sqrt{C^2 + (Rp\beta^3/t)^2}$. After a small correction for self-absorption in the steel cylinder this yields relative gamma-ray intensity. If the source-radiator geometry, radiator size and baffle settings are kept constant, radiators of different thickness and material may be used and gamma-ray intensities on the same relative scale will be obtained by using the appropriate $1/\tau p\beta^3$ and $\sqrt{C^2 + (Rp\beta^3/t)^2}$ factors. Thus we have available a reliable means of measuring gamma-ray intensities from 80 kev upward. In the region from 80 to 200 kev antimony radiators are as good or better than gold. For the region from 200 to 400 kev gold is better than antimony or uranium. Above 400 kev uranium gives greater sensitivity.

This thesis has made a contribution to the problem of measuring gamma-ray intensities with photon energies<200 kev. It also describes how the ion ejection technique can be used to obtain thin beta sources.

REFERENCES

Artna, A., (1961); Ph.D. Thesis, McMaster University.

Bakker, C. J., Segrè, E., (1951); Phys. Rev. 81, 489.

Barr, L. W., Blackburn, D. A., (1959); J. Sci. Instr. 36, 197.

Carswell, D. J., Milsted, J., (1957); J. Nucl. Energy 4, 51.

Chen, J. J. L., Warshaw, S. D., (1951); Phys. Rev. 84, 355.

Compton, A. H., (1922); Bull.Natl. Research Council 4, No. 20.

Deutsch, M., Elliott, L. G., Evans, R. D., (1944); Rev. Sci. Instr. 15, 178.

Dodson, R. W., Graves, A. C., Helmholtz, L., Hufford, D. L., Potter, R. M., Povelites, J. G., (1952); "Miscellaneous Physical and Chemical Techniques of the Los Alamos Project", ed. by Graves and Froman, McGraw-Hill.

Heitler, W., (1944); "The Quantum Theory of Radiation", Oxford University Press.

Hultberg, S., (1959); Arkiv Fysik 15, 307.

Johns, M. W., Waterman, H., MacAskill, D., Cox, C. D., (1953); Can. J. Phys. 31, 225.

Novakov, T., Mladjenović, M., (1956); Rev. Sci. Instr. 27, 415.

Parker, W., (1959); Nucl. Instr. and Methods 5, 142.

Parker, W., DeCroës, M., Sevier, K., Jr., (1960); Nucl. Instr. and Methods 7, 22.

Siegbahn, K., Svartholm, N., (1946); Nature 157, 872.

Siegbahn, K., (1955); "Beta- and Gamma-Ray Spectroscopy", Interscience Publishers Inc., New York.

Sliv, L. A., Band, I. M., (1956); "Coefficients of Internal Conversion of Gamma Radiation", The Academy of Science of the U. S. S. R.

White, P., Millington, G., (1928); Proc. Roy. Soc. A120, 701.